MASTER COPY KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
May 14, 1997

3. REPORT TYPE AND DATES COVERED
Final Technical, 6/1/93 - 2/15/97

4. TITLE AND SUBTITLE
Unified Methodology for Integrated Circuit Printed Antenna Array Design

5. FUNDING NUMBERS
DAAH04-93-G-0228

6. AUTHOR(S)
Nicolaos G. Alexopoulos

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, Los Angeles
Department of Electrical Engineering
405 Hilgard Avenue
Los Angeles, CA 90095

8. PERFORMING ORGANIZATION REPORT NUMBER
A93-0769C-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 31154.18-EL

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This research entailed the development of a unified methodology for integrated circuit, printed antenna, and printed antenna array design. Microwave antenna performance optimization may be achieved by shaping the antenna properly, as well as with the correct antenna excitation design. This final report presents a methodology for the design of 3-D microstrip fed arbitrarily shaped aperture and patch antennas in a multilayered medium. It includes the design of antenna excitation either through parasitic coupling, or through a via hole transition from a microstrip line. Comparison of numerical results with experimental data shows good agreement. A methodology for the design of multiple via-hole and air-bridge transitions of arbitrary shape in multilayered multiport microstrip circuits is also presented. Application of multiple via holes to the design of microstrip filters and other devices will be discussed. To properly describe the current along the vertical post, the simple pulse function with triangular cross section is used in the moment method analysis. Circularly and rectangularly shaped vertical transitions are analyzed for several practical applications. Comparisons of numerical results with experimental and available data again shows good agreement.

14. SUBJECT TERMS
Design of microwave integrated circuits, printed antennas, and printed antenna arrays utilizing full-wave MoM simulation.

15. NUMBER OF PAGES
16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Contents

List of Figures

1. Research Outline

With the merits of low profile, low cost and compact size, microstrip elements are useful for applications in microwave antennas and antenna arrays. They can be used as the radiating element of a MIC/MMIC design in aircraft/satellite communications [1], in missile and rocket [2] antenna systems, as well as many other applications. Due to substantial improvements in fabrication technologies, microstrip elements can now be designed as useful antennas well into the millimeter-wave range. Compact size and large scale integration of electronic devices have been driving the trend towards a multilayered interconnection system. Via holes and other vertical shunt posts, such as bond wires and air bridges, are increasingly important in microwave integrated circuit/monolithic microwave integrated circuit (MIC/MMIC) design. Via holes are used to connect parallel microstrip lines for signal transmission between different layers. Vias can be modeled by lumped circuit elements at lower frequencies. The equivalent circuits of vias based on the quasi-static analysis have been investigated by Wang *et.al.* [27],[28]. At higher frequencies the propagation characteristics of via holes have a stronger electromagnetic effect on the performance of devices, therefore, rigorous analysis is necessary to predict frequency response correctly.

A variety of full-wave design analyses have been reported over the past two decades [3] [4]. These techniques include finite-difference time-domain (FDTD) method, finite-element method (FEM), the method of lines (MOL), transmission line matrix (TLM), and integral equation (IE) formulations. Using reciprocity, Pozar [5] analyzed microstrip fed rectangular aperture and aperture coupled patch antennas. The most rigorous and general method is the integral equation formulation. It is based on the electric and magnetic-field integral equations (EFIE/MFIE) governed by the unknown current distributions on the microstrips and apertures. However, the EFIE/MFIE formulations suffer from either the highly singular behavior in the spatial domain, or the long computation time in the spectral domain. A modification of the EFIE/MFIE named the mixed-potential integral equation (MPIE), is formulated in the spatial domain. It was first introduced by Harrington [6], and has been extensively used for the analysis of wire antennas. Mosig [3],[7] and Michalski [8],[9] have applied MPIE models to planar microstrips. Chen *et. al.* [10] has applied the MPIE to model apertures in a ground plane.

In this research, a combined MPIE-EFIE formulation was developed to solve 3-D multi-layered circuits with arbitrary shape. First, the spectral-domain multi-layered Green's function was derived analytically by applying the wave matrix method [11] [12]. A hybrid complex image method (CIM) [13]-[16] and an efficient numerical integration algorithm [17] were implemented to evaluate the spatial-domain Greens' function through the Sommerfeld-type integral. Triangular basis functions [18] were used to expand the electric current distributions on the microstrip line, patch antenna, and the fictitious magnetic current distribution over the aperture. The simple pulse function with triangular cross section was adopted here to model the vertical electric current along the vias. The method of moments was then applied to solve the integral equation pertinent to the modeling of our problem. The MPIE formulation was used to evaluate the self-coupling terms of planar subdomains as well as the mutual-coupling terms of planar and vertical cells. The self-coupling submatrix due to vertical posts is calculated from the EFIE formulation since the analytic integration over the vertical basis function can alleviate the EFIE's singularity. The details of the matrix equation can be found in our previous work [10] [19].

A generalized three-dimensional (3-D) multilayered microstrip circuit is shown in Fig. 1. The medium is assumed to be infinite in the x-y plane , and the microstrip patterns are assumed to be of infinitesimal thickness. Both the upper and lower ground planes are removable to represent

either a shielded, semi-open, or open structure. Multiple vias as well a air-bridges are used to connect different microstrips. Grounded vias are also applied to achieve the short effect. The combined MPIE-EFIE methodology presented in this research meshes the whole microstrip geometry with small triangular facets. The MPIE formulation is used to evaluate the self coupling terms of planar subdomains as well as the mutual coupling between planar and vertical cells. The self coupling submatrix due to vertical posts is calculated from the EFIE formulation.

2. Numerical Results and Discussion

Five applications are discussed in this section. All computations are performed on the cluster system of IBM RS/6000's in the UCLA Office of Academic Computing Center.

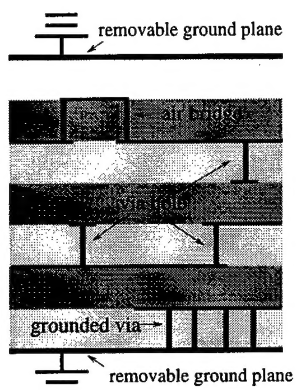

Figure 1: Generic via-hole and air-bridge transitions in a multilayered medium.

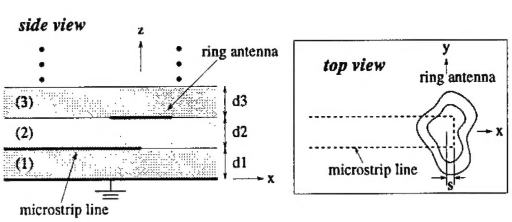

Figure 2: Arbitrary shaped ring-type antenna.

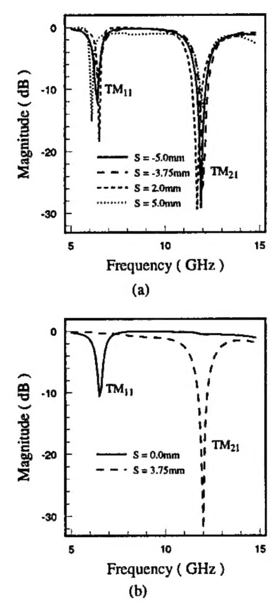

Figure 3: Return loss of a circular ring with different overlap coupling length: (a) Multiple mode excitation;(b) Single mode excitation; ϵ_1=ϵ_2=2.2, d_1=d_2=0.794mm, R_i=3.0mm, R_o=7.5mm, feedline width=2.25mm(50Ω), S is the overlap length with 0 at the center of the ring.

A. Electromagnetically-Coupled (EMC) Ring-Type Antenna

A popular type of microstrip antenna is the ring type shown in Fig. 2. To avoid the soldered probe-feed excitation, a microstrip feed line is embedded underneath to feed the ring element by electromagnetic coupling. Compared to circular disks, the ring antennas demonstrate larger bandwidth and smaller size by a proper choice of the annulus radii [21]-[24]. Fig.3 shows the return loss of an EMC circular ring antenna. The resonant frequencies of various modes and the lowest reflection will be changed by adjusting the overlap length between the feedline and the ring. Fig.3 (a) shows that most coupling lengths can excite two modes, namely TM_{11} and TM_{21} [23]-[25], but Fig.3(b) shows that for some specific lengths only one mode can be excited. This property can be exploited to design a radiator which can operate at single or multiple modes.

B. Via-Hole Application in Antenna Design

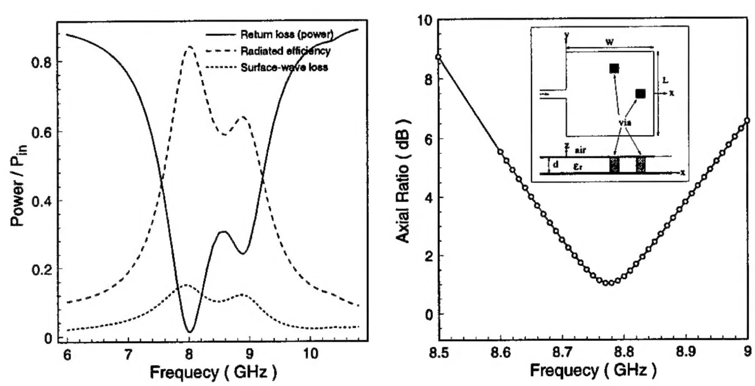

Figure 4: A grounded edge-fed rectangular patch antenna. Left: power distribution versus frequency: Right: axial ratio near 8.78 GHz. The antenna dimensions: d=1.575, W=L=12.7,line width=1.27,via size=1.27 x 1.27, via positions: (6.985,3.81),(10.795,0.0), ϵ_r=2.33. All units in mm.

Our second example is an edge-fed rectangular patch antenna grounded by two vias . The vias provide circular polarization and improved bandwidth by enhancing the coupling effects. The structure and analyzed results are shown in Fig.4. The planar structure is introduced in [20] with the analysis of power distribution by the spectral domain method. Addition of these vias shifts the resonant frequency from 7.2 GHz [20] to 8.0 GHz with linearly polarized radiation (AR $>$ 20 dB). This also introduces another resonance at 8.78 GHz with circularly polarized radiated field (AR $<$ 1 dB). The perturbation of the grounded vias makes the radiating element resonant along both the x and y directions.

C. Dual-Slot Coupled Circular Patch Antenna

Our third example is a dual-slot coupled circular patch (DSCCP) antenna as shown in Fig.5. This type of antenna was proposed by Shoki *et. al.*[26] with a stripline feed. Comparison with their measured data is excellent, as demonstrated in Fig. 6 (Left). However, with a uniform microstrip feed line, an input impedance match at the center frequency is not obtained as the dashed line in

Fig.6 (Right) indicates. We design and implement a quarter-wavelength microstrip transformer to obtain a good match as the solid line in Fig.6 (Right) shows. A near 90% radiation efficiency is also obtained.

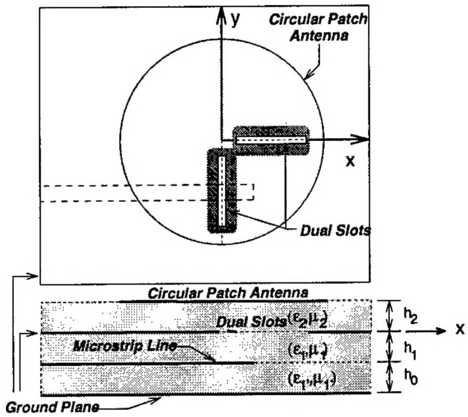

Figure 5: Configuration of a DSCCPA Antenna.

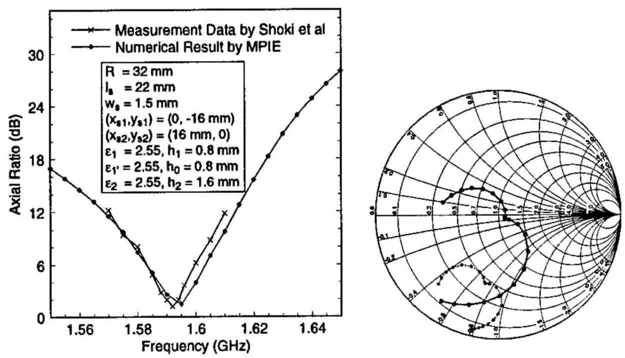

Figure 6: (Left)Comparison of axial ratio for a stripline fed DSCCP antenna between this work and [26]. (Right) Input impedance with and without a quarter wavelength transformer.

D. Grounded Via in an Infinite Microstrip Line

The next example is an infinite microstrip line grounded by a via, which was presented in [32] by using the planar waveguide model.

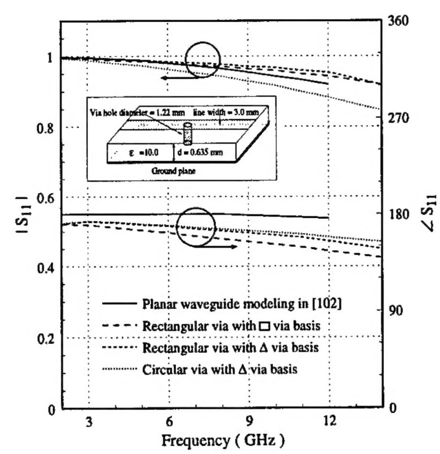

Figure 7: Magnitude and phase of S_{11} for an infinite microstrip line with ground via, $\epsilon_r = 2.2$, thickness = 0.635mm, line width = 3.0mm, via hole diameter = 1.22mm

The structure and analyzed results are shown in Fig.7 . Three different simulations are

investigated: 1) rectangular ground via expanded by one vertical current basis function with a rectangular cross section; 2) rectangular ground via expanded by two vertical current basis functions with triangular cross section; 3) circular ground via expanded by eight vertical current basis functions with triangular cross section. The reference plane is along the center of the ground via. All cases show that the current flows down to the ground plane, and a good short can be achieved over a broad frequency range.

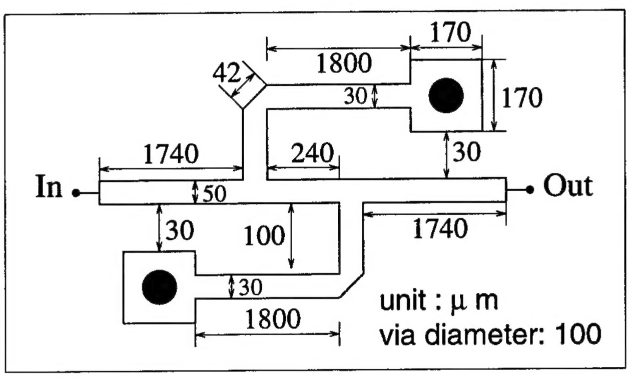

Figure 8: Geometry of bandpass filter with two via hole grounds (substrate height = 125μm and dielectric constant = 12.9).

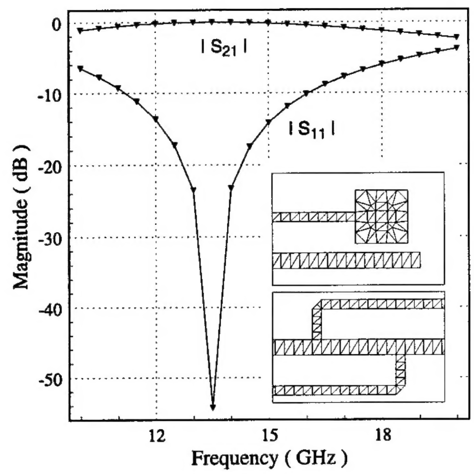

Figure 9: S-parameters of bandpass filter with two via grounds. Inset shows the triangular mesh.

E. Vias in Filter Design

Our last example incorporates two via-hole grounds as shown in Fig.8. Two metered-bend lines with rectangular pads are connected to the main transmission line. Each pad is grounded by a circular via hole with a 100-μm diameter. The triangular mesh is shown in the inset of Fig.9. Eighteen triangular cells are used to expand the vertical current for each via hole. The total number of unknowns is 555, and the CPU time is about 39.2 s per frequency point. Compared to 444s/freq for the Microwave Explorer 1.11 on HP730 [33], out algorithm is much more efficient. The simulated results are shown for lossless layers and perfectly conducting microstrip lines in Fig.9. The resonant frequency is predicted well as 13.5 GHz [33].

3. List of Manuscripts

1. T.-S. Horng, C.-C. Wang and Nicolaos G. Alexopoulos, "Microstrip Circuit Design Using Neural Networks," *IEEE MTT-S International Microwave Symposium,*, vol. 1, Atlanta, Georgia, pp. 413-416, May, 1993.
2. Tzyy-Sheng Horng and Nicolaos G. Alexopoulos, "Corporate Feed Design for Microstrip Arrays," *IEEE Trans. Antennas Propagat.*, vol. AP-41, pp. 1615-1624, Dec. 1993.
3. G. E. Antilla and Nicolaos G. Alexopoulos, "Scattering from Complex Three-Dimensional Geometries by a curvilinear Hybrid Finite-Element-Integral Equation Approach," *Journal of the Optical Society of America A*, vol. 11, pp. 1445-1457, April 1994.
4. I. Y. Hsia and N. G. Alexopoulos, "Electromagnetically Coupled Dipole Antennas in Nonreciprocal Microstrip," *IEEE Trans. Antennas Propagat.*, accepted to be published, 1994.
5. Huan-Chang Liu, Tzyy-Sheng Horng and Nicolaos G. Alexopoulos, "Radiation of Printed Antennas with a Coplanar Waveguide Feed," *IEEE Trans. Antennas Propagat.*, accepted to be published, 1994.
6. Jind-Yeh Lee, Tzyy-Sheng Horng and Nicolaos G. Alexopoulos, "Analysis of Cavity-Backed Aperture Antenna with a Cover (Superstrate)," *IEEE Trans. Antennas Propagat.*, accepted to be published, 1994.
7. Owen Fordham, Ming-Ju Tsai and N. G. Alexopoulos, "Electromagnetic synthesis of overlap-gap-coupled microstrip filters," *IEEE MTT-S International Microwave Symposium,* vol. 3, Orlando, Florida, pp. 1199-1202, May 1995.
8. Ming-Ju Tsai and Nicolaos G. Alexopoulos, "Electromagnetically coupled microstrip ring-type antennas of arbitrary shape," *IEEE AP-S International Symposium,* vol. 1, Newport Beach, California, pp. 684-687, June 1995.
9. Ming-Ju Tsai and Nicolaos G. Alexopoulos, "Modeling Planar Arbitrarily-shaped Microstrip Elements in Multi-layered Media," submitted to *IEEE Trans. Microwave Theory Tech.*.
10. Chinglung Chen and Nicolaos G. Alexopoulos, "Spectral Domain Analysis of Microstripline Fed Arbitrarily-Shaped Aperture Antennas," *IEEE AP-S International Symposium,* vol. 1, Seattle, Washington, pp. 158-161, June, 1994.
11. Owen Fordham, Ming-Ju Tsai and N. G. Alexopoulos, "Electromagnetic Synthesis of Overlap-Gap-Coupled Microstrip Filters," *IEEE MTT-S International Microwave Symposium,* vol. 3, Orlando, Florida, pp. 1199-1202, May 1995.
12. Chinglung Chen and Nicolaos G. Alexopoulos, "Triplate-Fed Arbitrarily-Shaped Annular Ring Slot Antennas," *IEEE AP-S International Symposium,* vol. 4, Newport Beach, California, pp. 2066-2069, June 1995.
13. Chinglung Chen and Nicolaos G. Alexopoulos, "Radiation by Aperture Antennas of Arbitrary Shape Fed by a Covered Microstrip Line," *IEEE AP-S International Symposium,* vol. 4, Newport Beach, California, pp. 2070-2073, June 1995.
14. Franco De Flaviis, Ming-Ju Tsai, Shih-Chang Wu and Nicolaos G. Alexopoulos, "Optimization of microstrip open end," *IEEE AP-S International Symposium,* vol. 3, Newport Beach, California, pp. 1490-1493, June 1995.

15. Ming-Ju Tsai, Chinglung Chen and Nicolaos G. Alexopoulos, "Multi-Layered Structure Green's Function for Microstrip Elements of Arbitrary Shape," *Proceedings of the International Conference on Electromagnetics in Advanced Applications (ICEAA 95),* pp. 3-5, Torino, Italy, September 1995.
16. Chinglung Chen and Nicolaos G. Alexopoulos, "Modeling Microstrip Line Fed Slot Antennas with Arbitrary Shape," *Electromagnetics,* vol. 15, no. 5, pp. 567-586, Sep.-Oct., 1995.
17. Chinglung Chen, William E. McKinzie and Nicolaos G. Alexopoulos, "Stripline Fed Arbitrarily-Shaped Printed Aperture Antenna," submitted to *IEEE Trans. Antennas Propagat.*. (07/16/95)
18. Ming-Ju Tsai, Tzyy-Sheng Horng and Nicolaos G. Alexopoulos, "Via Holes, Bond Wire, and Shorting Pin Modeling for Multi-Layered Circuits," *IEEE MTT-S International Microwave Symposium,* vol. 3, San Diego, California, pp. 1777-1780, May, 1994.
19. Ming-Ju Tsai and Nicolaos G. Alexopoulos, "Via Hole Modeling for an Electromagnetically Coupled Patch Antenna," *IEEE AP-S International Symposium,* vol. 2, Seattle, Washington, pp. 1194-1197, June, 1994.
20. Tzyy-Sheng Horng, Ming-Ju Tsai, Ching-Lung Chen and Nicolaos G. Alexopoulos, "The Influence of Metallization Thickness on a Microstripline-Fed Patch Antenna," *IEEE AP-S International Symposium,* vol. 2, Seattle, Washington, pp. 940-943, June, 1994.
21. Nicolaos G. Alexopoulos, Ming-Ju Tsai and Tzyy-Sheng Horng, "Interconnect Modeling: Discontinuities and Spurious Effects," *EMC '94 Roma. International Symposium on Electromagnetic Compatibility,* vol. 2, pp. 566-570, Rome, Italy, Sep. 1994.
22. Ming-Ju Tsai and Nicolaos G. Alexopoulos, "Proximity Coupled Microstrip Elements and Interconnects of Arbitrary Shape in Multilayered Media," *IEEE MTT-S International Microwave Symposium,* vol. 2, Orlando, Florida, pp. 475-478, May 1995.
23. Chinglung Chen, Ming-Ju Tsai, and Nicolaos G. Alexopoulos, "Mutual Coupling Between Microstrips Through A Printed Aperture of Arbitrary Shape in Multi-Layered Media," *IEEE Microwave and Guided Wave Letters,* vol. 6, no. 5,pp. 202-204, May 1996.
24. Ming-Ju Tsai, Chinglung Chen, and Nicolaos G. Alexopoulos, "Multiple Arbitrary Shape Via-Hole and Air-Bridge Transitions in Multilayered Structures," accepted to be published in *IEEE 1996 MTT-S International Microwave Symposium.* (06/19/95)
25. Chinglung Chen, Ming-Ju Tsai, and Nicolaos G. Alexopoulos, "Optimization of Aperture Transitions for Multi-Port Microstrip Circuits," accepted to be published in *IEEE 1996 MTT-S International Microwave Symposium.* (06/19/95)
26. Ming-Ju Tsai, Chinglung Chen, and Nicolaos G. Alexopoulos, "Three-Dimensional Modeling for Electromagnetically Coupled Microstrip Antennas of Arbitrary Shape," accepted to be published in *IEEE 1996 AP-S International Microwave Symposium.* (07/23/96)
27. Chinglung Chen, Ming-Ju Tsai, and Nicolaos G. Alexopoulos, "Microstrip Line Fed Slot, Slot-Coupled Patch Antennas,and Mutual Coupling Study in Array Applications," accepted to be published in *IEEE 1996 AP-S International Microwave Symposium.* (07/23/96)
28. Ming-Ju Tsai and Nicolaos G. Alexopoulos, "Via hole and parasitically coupled microstrip antennas of arbitrary shape on multi-layered substrates," submitted to *Electromagnetics.* (04/15/96)

29. Chinglung Chen and Nicolaos G. Alexopoulos, "Arbitrarily-Shaped Slot-Coupled Microstrips and Their Application in Microwave Integrated Circuit and Antenna Design," submitted to *Electromagnetics.* (05/01/96)
30. Ming-Ju Tsai, Chinglung Chen and Nicolaos G. Alexopoulos, "Efficient Green's Function for the Modeling of Interconnects and Microstrip Elements in Multi-Layered Media," submitted to *IEEE Microwave and Guided Wave Letters.* (05/08/96)

4. Scientific Personnel

1. George Antilla Ph.D. Electrical Engineering June 1993.
2. Ming-Ju Tsai, M.S. and Ph.D. Electrical Engineering December 1993 and June 1996 respectively.
3. Ching-Lung Chen, M.S. and Ph.D. Electrical Engineering December 1993 and June 1996 respectively.
4. Owen Fordham
5. Franco DeFlaviis
6. Raul R. Ramirez
7. William M. Merrill M.S. Electrical Engineering December 1996.

References

[1] G. G. Sanford, "Conformal microstrip phased array for aircraft tests with ATS-6," *IEEE Trans. on Antenna Propagat.*, vol. AP-26, no. 5, pp. 642-646, Sep. 1978.

[2] C. W. Garvin, R. E. Munson, L. T. Ostwald, and K. G. Schroeder, "Missile base mounted microstrip antennas," *IEEE Trans. on Antenna Propagat.*, vol. AP-25, no. 5, pp. 604-610, Sep. 1977.

[3] "Numerical Techniques for Microwave and Millimeter-wave Passive Structures," edited by T. Itoh, John Wiley & Sons Inc., New York, 1989.

[4] "Analysis and Design of Planar Microwave Components," edited by K.C. Gupta and M.D. Abouzahra, IEEE Press, New York, 1994.

[5] D. R. Pozar, "A reciprocity method of analysis for printed slot and slot-coupled microstrip antennas," *IEEE Trans. on Antenna Propagat.*, vol. AP-34, No. 12, pp. 1439-1446, Dec. 1986.

[6] R. F. Harrington, *Field Computation by Moment Methods*, Macmillan, New York, 1968.

[7] J. R. Mosig and F.E. Gardiol, "General integral equation formulation for microstrip antennas and scatterers," *IEE proc. H*, vol. 132, no. 7, pp. 424-432, Dec. 1985.

[8] K. A. Michalski, "The mixed-potential electric field integral equation for objects in layered media," *Arch. Elek. Übertragung.*, vol. 39, pp. 317-322, Sep.-Oct. 1985.

[9] K. A. Michalski, and D. Zheng, "Electromagnetic scattering and radiation by surfaces of arbitrary shape in layered media, part I: theory ," *IEEE Trans. on Antenna Propagat.*, vol. AP-38, pp. 335-344, March 1990.

[10] C. Chen and N. G. Alexopoulos, "Modeling microstrip line fed slot antennas with arbitrary shape," *Electromagnetics*, Vol. 15, No. 5, pp. 567-586, Sep.-Oct. 1995

[11] W. C. Chew, "Waves and Fields in Inhomogeneous Media," Chapter 2, Van Nostrand Reinhold, New York, 1990.

[12] M.-J. Tsai, C. Chen and N. G. Alexopoulos, "Multi-layered structure Green's function for microstrip elements of arbitrary shape," *Proceedings of the International Conference on Electromagnetics in Advanced Applications (ICEAA 95)*, pp. 3-5, Torino, Italy, September 1995.

[13] D. G. Fang, J. J. Yang, D. G. Fang, and G. Y. Delisle, "Discrete image theory for horizontal electric dipoles in a multilayered medium," *IEE proc. H*, vol. 135, pp. 297-303, Oct. 1988.

[14] Y. L. Chow, J. J. Yang, D. G. Fang, and G. E. Howard, "Closed-form spatial Green's function for the thick substrate," *IEEE Trans. on Microwave Theory Tech.*, vol. MTT-39, no. 3, pp. 588-592, Mar. 1991.

[15] M. I. Aksun, and R. Mittra, "Derivation of closed-from Green's functions for a general microstrip geometry," *IEEE Trans. on Microwave Theory Tech.*, vol. MTT-40, no. 11, pp. 2055-2062, Nov. 1992.

[16] G. Dural and M. I. Aksun, "Closed-form Green's functions for general sources and stratified media," *IEEE Trans. on Microwave Theory Tech.*, vol. MTT-43, no. 7, pt. 1, pp. 1545-1552, July 1995.

[17] M.-J. Tsai, C. Chen and N. G. Alexopoulos, "Efficient Green's function for the modeling of interconnects and microstrip elements in multi-layered media," submitted to *IEEE Trans. Microwave Theory Tech..* (08/01/95)

[18] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antenna Propagat.*, vol. AP-30, pp. 409-418, May 1982.

[19] M.-J. Tsai, C. Chen and N. G. Alexopoulos, "Air-bridge transitions in multilayered structures," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-40, No. 12, pp. 2504-2511, Dec. 1996.

[20] T. -S. Horng, S. -C. Wu, H. -Y. Yang, and N. G. Alexopoulos, "A Generalized Method for Distinguishing between radiation and surface-wave losses in microstrip discontinuities," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-38, No. 12, pp. 1800-1807, Dec. 1990.

[21] S. M. Ali, W. C. Chew, and J. A. Kong, "Vector Hankel transform analysis of annular-ring microstrip antenna," *IEEE Trans. on Antenna Propagat.*, vol. AP-30, no. 4, pp. 637-644, July 1982.

[22] W. C. Chew, "A broad-band annual-ring microstrip antenna," *IEEE Trans. Antenna Propagat.*, vol. AP-30, no. 5, pp. 918-922, Sep. 1982.

[23] I. J. Bahl and S. S. Stuchly, "Closed-form expressions for computer-aided design of microstrip ring antennas," *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering*, vol. 2, no. 3, pp. 144-154, 1992.

[24] S. Mellah, M. Drissi, J. M. Floch and J. Citerne, "Theoretical and experimental investigation of smooth and discrete microstrip ring antennas," *IEEE AP-S Int. Symp. Dig.*, pp. 2196-2199, 1992.

[25] Y. T. Lo, D. Solomon, and W. F. Richards, "Theory and experiment on microstrip antennas," *IEEE Trans. on Antenna Propagat.*, Vol. AP-27, No. 2, pp. 137-145, Mar. 1979.

[26] H. Shoki, K. Kawabata, and H. Iwasaki, "A circularly polarized slot-coupled microstrip antenna using a parasitically excited slot," *IEICE Transactions*, Vol. E 74, No. 10, pp. 3268-3273, Oct. 1991.

[27] T. Y. Wang, R. F. Harrington, and J. R. Mautz , " The equivalent circuit of a via," *Trans. Soc. Comput. Simulation*, Vol. 4, pp. 97-123, April 1987.

[28] —, "Quasistatic analysis of a microstrip via through a hole in a ground plane," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-36, No. 6, pp. 1008-1013, June 1988.

[29] J. R. Mosig, "Arbitrarily shaped microstrip structures and their analysis with a mixed potential integral equation", *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-36, No. 2, pp. 314-323, Feb. 1988.

[30] M. -J Tsai and N. G. Alexopoulos, "Proximity coupled microstrip elements and interconnects of arbitrary shape in multilayered media", in *IEEE MTT-S Int. Microwave Symp.*", Orlando, FL, 1995, Vol. 2, pp. 475-478.

[31] —, "Electromagnetically coupled microstrip ring-type antennas of arbitrary shape," in *IEEE AP-S Int. Symp.*, Newport Beach, CA, 1995, Vol. 1, pp 684-687.

[32] K. L. Finch and N. G. Alexopoulos, "Shunt posts in microstrip transmission lines," *IEEE Trans. Microwave Theory Tech.*, Vol. MTT-38, No. 11, pp. 1585-1594, Nov. 1990.

[33] "MIC Simulation Column," *Int. J. Microw. Millimeter-Wave Comput. Aided Eng.*, Vol. 3, No. 1, p. 76, 1993.